TO STUDY THE EFFECT OF STRAIN RATE ON TENSILE PROPERTIES AND HIGH CYCLE FATIGUE BEHAVIOUR OF IF STEEL

THIS THESIS IS SUBMITTED IN THE PARTIAL FULLFILMENT OF THE REQUIREMNT FOR THE DEGREE OF BACHELOR OF TECHNOLOGY

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2013

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **“TO STUDY THE EFFECT OF STRAIN RATE ON TENSILE PROPERTIES AND HIGH CYCLE FATIGUE BEHAVIOUR OF INTERSTITIAL FREE STEEL ”** submitted by **Dilip Kumar Nayak(109mm0482)** and **Rajesh Kumar Palai(109mm0483)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** Degree in **Metallurgical and Materials Engineering** at **National Institute of Technology, Rourkela** is an original work carried out by them under my supervision and guidance.

The matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree.

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ABSTRACT

Interstitial Free steels find their applications in various industries including automobile. Their extensive use in industries are due to their excellent formability, weldability and toughness. These materials are usually exposed to various strain rates during service. In the present investigation an attempt has been made to study the effect of strain rate. And it has been found that as the strain rate of loading increases the strength of the material increases but the ductility decreases.

Though enough information are available on the effect of low cycle fatigue on this type of material, however in many cases they are also exposed to high cycle loading condition. Therefore an attempt has been made to study the effect of high cycle fatigue with σ_{max} close to the yield strength of the material. And a relation has been established between the stress ratio and the number of cycles to failure

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Chapter 1

INTRODUCTION

1. Introduction

1.1. Steel

Steel is an alloy of not only iron but also other elements, like carbon. Mainly when carbon is the primary alloying element, its constituent in the steel ranges between 0.002% and 2.1% by weight. The following elements are always incorporated in steel: carbon, manganese, phosphorus,sulphur, silicon, and minute traces of oxygen, nitrogen and aluminium. Addition of alloying element which modify the characteristics of steel as per the increasing requirement include: manganese, nickel, chromium, molybdenum, boron, titanium, vanadium and niobium

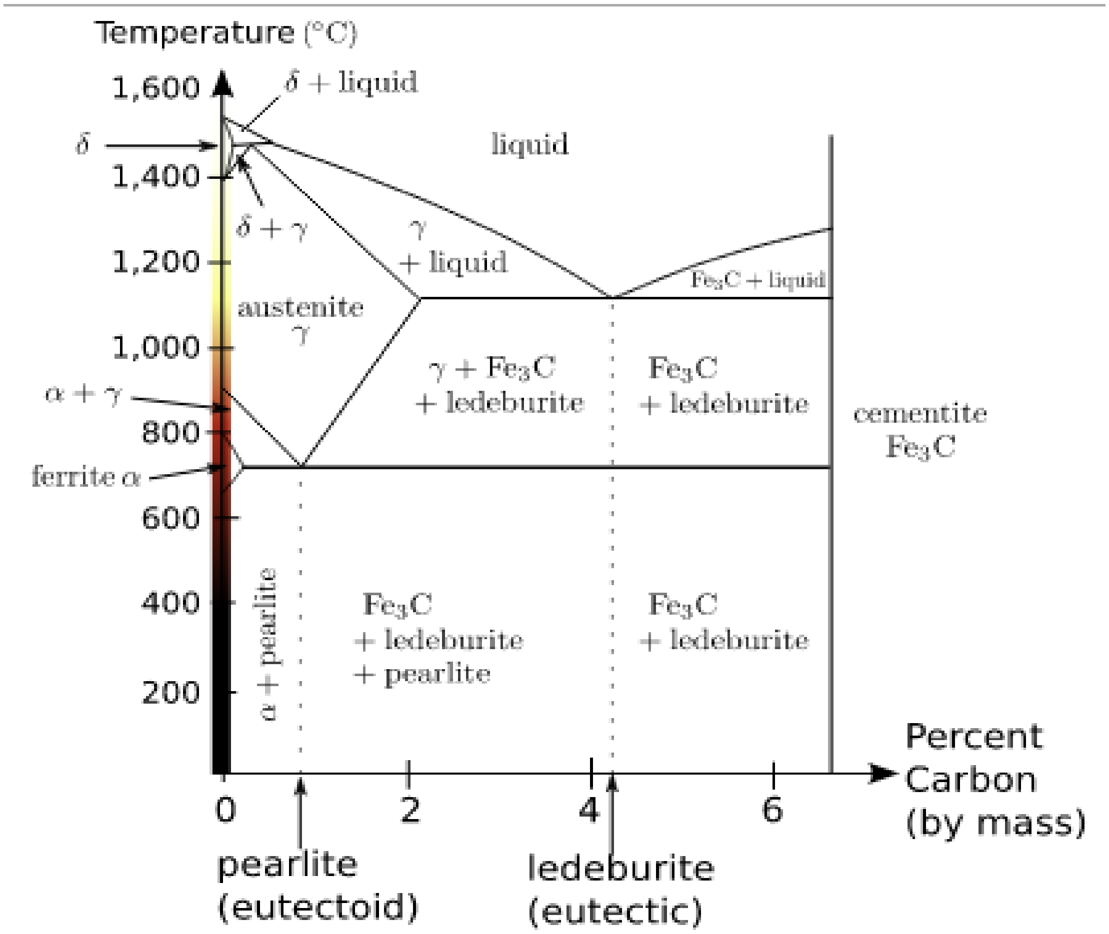

Fig no 1.1 (fe-c phage diagram)

Additional materials are often added to the iron/carbon mixture to produce steel with properties meeting the increasing demands of day to day market. Nickel and manganese in steel strengthens tensile strength and the austenite form of the iron-carbon solution become more stable, chromium increases hardness and fusion temperature, and vanadium also increases hardness while reducing the effects of metal fatigue.

To inhibit corrosion, at least 11% chromium is added to steel so that a hard oxide forms on the metal surface; this is known as stainless steel. Tungsten mainly interferes with the formation of cementite, allowing preferentially formation of martensite at slower quench rates, leading in production of high speed steel. In addition to it, nitrogen, sulfur and phosphorus make steel more brittle, so these commonly found elements are a must to be removed from the ore during processing.

The density of steel depending on the alloying constituents usually ranges between 7,750 and 8,050 kg/m3 (484 and 503 lb/cu ft), or 7.75 and 8.05 g/cm3 (4.48 and 4.65 oz/cu in).

1.2. Interstitial free steel(ifs)

Steel manufactured with very low amounts of interstitial elements (primarily carbon and nitrogen) with small amounts of titanium or niobium added to tie up the remaining interstitial atoms. When free interstitial elements are not present, these steels which are very ductile and soft, will not bake harden or age, and will never form strain (Luder's) lines during forming due to the absence of YPE (yield point elongation)

Interstitial-free (IF) steels constitute one of the major groups of bcc steels used in the automotive industry for forming thin gauge sheet body panels

Sheet metal is a critical material for vehicle design, due to its design versatility and manufacturability. Low carbon sheet steel has long been the workhorse material in consumer industries because it can be stamped into inexpensive, complex components at very high production rates. There has been a continuing trend towards development of materials with improved formability, which led to development of deep drawing quality (DDQ) and extra deep drawing quality (EDDQ) steel sheets and several nonferrous alloys. In recent decades, the development of interstitial free (IF) steel satisfies the stringent demand of automobile manufactures due to their excellent formability . These interstitial free steel sheets are replacing other materials for very critical forming applications. Interstitial-free steels are produced by the addition of titanium and/or niobium to an extra low carbon grade to precipitate interstitial carbon and nitrogen atoms[17] .

Use of galvanised steel increased because of its high corrosion resistance. Galvanizing is the process in which a zinc layer that is metallurgicaly bonded to the iron or steel's surface. Primarily being used for corrosion protection, zinc coating is also applied to sheets for others reasons, including solderability, temperature resistance, lubrication and paint ability. The hot dip galvanizing is the most widely used galvanizing process, which involves immersing very clean steel sheet, as a continuous ribbon, into a zinc molten bath at temperature 450–460 °C.

The composition of if steel sheet is C ~ 0.0035, Mn ~ 0.079, S ~ 0.0089, P ~ 0.0109, Si ~ 0.006, Al ~ 0.0359, Ti ~ 0.067, N ~ 0.003[17].

In recent years the amount of research on IF steels has increased, primarily focussed at studies of precipitation and segregation behaviour related to cold work embrittlement (CWE) during deep drawing . Relatively few studies have focused on fatigue performance and most of those have considered issues other than crack paths and the occurrence of IG cracking during fatigue. Daniélou et al. explicitly considered the mechanisms of cyclic plasticity at several different plastic deformation amplitudes and strain rates. In their steel, initiation of fatigue cracks was observed to be both intergranular and transgranular at ambient temperature (293 K) but the intergranular region was reportedly confined to cracks <50 μm in length. Islam and Tomota reported the occurrence of extensive IG faceting on the fatigue fracture surfaces but ascribed this to environmentally-induced hydrogen embrittlement and to grain boundary segregation of phosphorous. Most studies have considered only a fairly confined range of IF steels and experimental conditions.

1.3.Fatigue

Repeated cycling of the load causes metal fatigue. Due to fluctuating stresses and strains on the material it is a progressive localized damage. The cracks get initiated and propagate in regions where the strain is most severe.

Considering metals and alloys, when macroscopic or microscopic discontinuities are generally not present, it commences with dislocation movements, finally forming persistent slip bands that nucleate short cracks.

The fatigue procedure generally consists of three stages [14]:

- Firstly crack initiation
- Continuous crack growth across the part
- Commending with sudden fracture of the remaining cross section

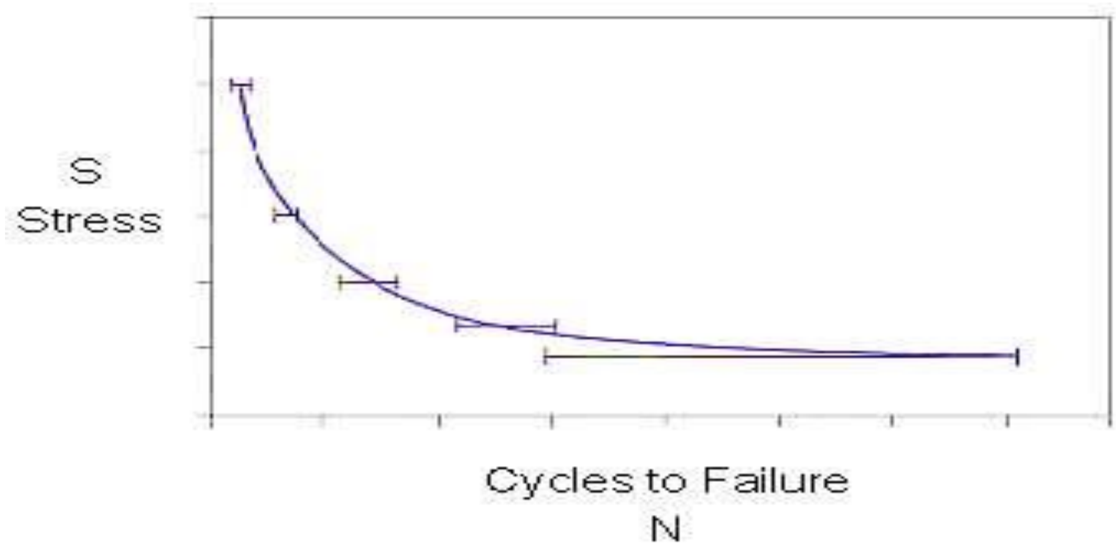

Fig no 1.2 (S-N Curve, showing increase in fatigue life with decreasing stresses.)

Different stages of fatigue can also be defined in more general terms from the perspective of mechanical behavior of crack growth. For an example, another division of the fatigue process is defined as follows:

- Nucleation (initiation of fatigue cracks)
- Structurally dependent crack growth rates (often called the “short crack” or “small crack” phase)
- Crack growth rates that can be defined by linear elastic fracture mechanics, elastic-plastic fracture mechanics, or fully plastic fracture mechanics.
- Final instability

The fatigue process has stages which is primarily equivalent to the first stages, except that crack propagation is expressed in terms of nucleation and crack growth rates is meant to include all processes leading up to crack initiation

Fatigue life ,Nf, is the no. of stress cycles of a specified character that a specimen can sustain before it fails due to specified nature

One way to predict fatigue life of materials is the Uniform Material Law (UML). UML was primarily developed to predict the fatigue life of aluminum and titanium alloys by the end of 20th century and further was also used to find the fatigue life of high-strength steels and cast iron. Also for some materials, there is a theoretical value for stress called a fatigue limit amplitude below the level of which the material will not fail for any no. of cycles. It is also endurance limit, or fatigue strength as per wish.

Stress Ratio is the ratio of the minimum to the maximum stress (Smin/Smax).

- If the stresses are fully reversed, then R = -1.
- If the stresses are partially reversed, R = a negative number less than 1.
- If the stress fluctuates between a maximum stress and no load, R = zero.
- If the stress fluctuates between two tensile stresses, R = a positive number less than1.

Variations in the stress ratios do significantly affect fatigue life. A substantial effect on fatigue failure is due to presence of mean stress. On addition of a tensile mean stress to the alternating stresses, failure of a component will occur at lower alternating stress than it generally does under a fully reversed stress.

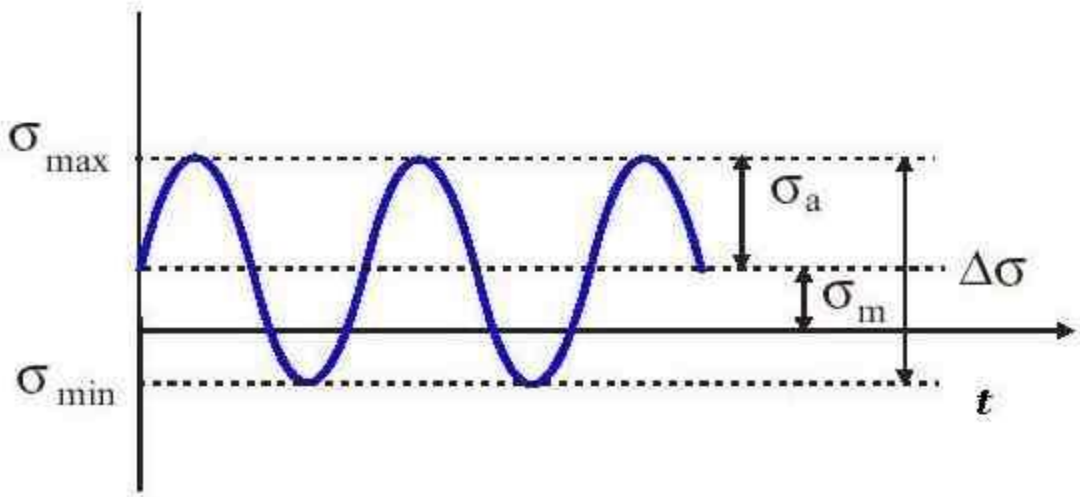

fig no 1.3

Fatigue failure is of two type

i. High cycle fatigue

ii. Low cycle fatigue

1.4.High cycle fatigue

When the fatigue occurs above 10^3 cycles (usually 10^4 or more), it is usually called High-cycle fatigue. The material is applied lower loads, usually less than 2/3 of the yield stress. The deformation is elastic deformation.

In high-cycle fatigue, materials performance is generally characterized by an S-N curve, also known as a Wohler curve . This is a graph of the magnitude of a cyclic stress (S) against the logarithmic scale of cycles to failure (N).

The progression of the S-N curve depends on many factors such as corrosion, temperature, and the presence of notches. The Goodman-Line is a method to estimate the influence of the mean stress on the fatigue strength [20].

As coupons sampled from a homogeneous frame will manifest variation in their number of cycles to failure, the S-N curve should more properly be an S-N-P curve capturing the probability of failure after a given number of cycles of a certain stress. Probability distributions, common in data analysis and in design against fatigue include the extreme value distribution, lognormal distribution, Birnbaum–Saunders distribution, Weibull distribution.

1.5. Strain rate

Strain is the amount of deformation that occurs when an object is placed under stress. Strain rate is calculated as the change in strain over the change in time. All materials generally undergo some change in their dimensions when exposed to stress. This deformation caused by stress can be fully reversible or permanent, depending on the stress applied.

Elastic strain starts when a material under stress returns to its original dimensions once the stress is removed. Plastic strain appears as the object has been exposed to very high levels of stress and will no longer return to its original shape after the stress is removed. The instantaneous reversal of elastic strain in many materials, means it occurs in insufficient duration of time. The deformation which is fully elastic, but occurs over time, is described in terms of the strain rate. For different materials strain rate varies widely, and often changes at different temperatures and applied pressures. Steel is such a material that returns to its original state immediately after applied stress is removed. Conversely, according to geology, stresses are applied over millions of years and the rate of strain in rock is typically very low. Thus a material whose rate of strain changes a large amount at different temperatures and pressures has high strain rate sensitivity [22].

This rate is also dependent on the applied force or stress . In many plastics, if a gradual stretching force is applied the material will elongate a large amount before it breaks. As the molecules in the plastic have enough time to reorient themselves and move past each other, causing the stretching to occur. Thus an impact or sudden force when applied to a plastic, will break it immediately like a brittle material. The very same plastic material will react very differently due to different rates of strain caused by the way the stress is applied.

Strain rate is measured in the laboratory using special test equipment that applies very precise cyclic loads to a sample, while measuring the deformation and recovery that occurs after the stress is removed for that specific load applied. As the strain rate of a material influences its behavior, it becomes thus mandatory to understand its sensitivity to the type of load, amount of stress, and temperature. Reflecting on the strain rate of a material will ensure that it meets the performance specifications as required for the application.

1.6.Tensile properties[16]

Tensile properties portray how the material will react to forces applied in tension.The test is a basic mechanical test in which a prepared specimen is loaded very carefully while measuring the applied cyclic load and the elongation of the specimendue to the load applied. The test is used to measure modulus of elasticity, elongation,elastic limit proportional limit,tensile strength, reduction in area, yield point, yield strength and other tensile properties . Load versus elongation is the result from tensile test which is then surveyed into a stress versus strain curve. The load-elongation curve will bear the same shape as the engineering stress-strain curve since both the engineering stress and the engineering strain are obtained by dividing the load and elongation by constant values (specimen geometry information),. The stress-strain curve generally portrays the relation of the applied stress to the resulting strain. An engineering stress-strain curve is shown below. It is depicted that the stress-strain curve increases continuously up to fracture if the true stress, depending on the actual cross-sectional area of the specimen, used.

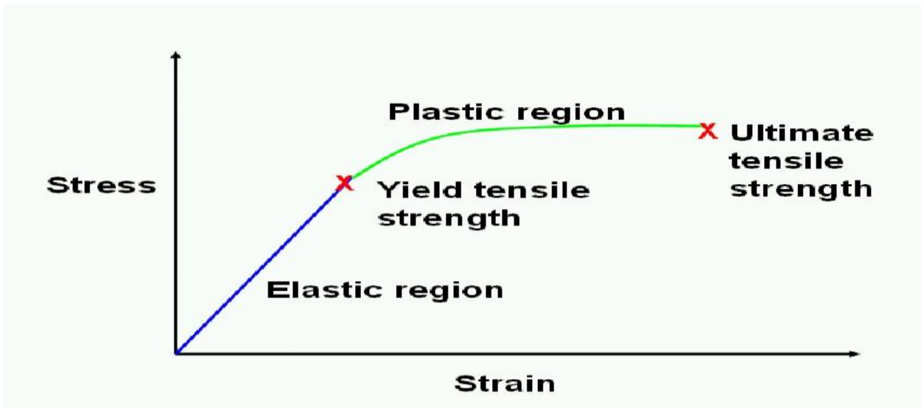

Fig no 1.4 (stress stain curve)

Chapter 2

LITERATURE REVIEW

Q. Y. Wang [1] made an attempt to characterize the high cycle fatigue behavior of high-strength spring steel wire by means of an ultrasonic fatigue test and analytical techniques. The fatigue strength of the steel wires between 106 and 109 cycles was determined at a load ratio R=−1. The experimental results show that fatigue rupture can occur beyond 107 cycles. For Cr–V spring wire, the stress–life (S–N) curve becomes horizontal at a maximum stress of 800 MPa after 106 cycles, but the S–N curve of the Cr–Si steel continues to drop at a high number of cycles (>106 cycles) and does not exhibit a fatigue limit, which is more correctly described by a fatigue strength at a given number of cycles. Experimental and analytical techniques were developed to better understand and predict high-cycle fatigue life in terms of crack initiation and propagation. The results show that the portion of fatigue life attributed to crack initiation is more than 90% in the high-cycle regime for the steels studied in this investigation.

M.D. Chapetti [2] studied the fatigue crack propagation from the surface and from internal inclusions is analyzed and modeled in high strength steels that show both types of crack initiation. Fatigue crack propagation lives of a crack initiated from the surface and from internal inclusions are estimated and analyzed. The high cycle fatigue life for a given crack range is estimated by: (a) defining material resistance to crack propagation as a function of crack length, and (b) assuming that the difference between the applied driving force and material resistance for crack propagation defines the effective driving force applied to the crack. If the crack growth rate as a function of this effective driving force is known for a given material, the high cycle fatigue life for a given crack length range can be estimated. The present model estimates reasonably well the fatigue life associated with crack initiated from the surface. On the other hand, the fatigue life of crack initiated from internal inclusions has an associated initiation life defined by a hydrogen assisted fatigue mechanism that represents a great part of the total fatigue life. In this case, the fatigue crack propagation life predicted by the model is a small part of the total fatigue life.

C.Michael Hudson [3] studied the effect of stress ratio on the fatigue behavior of 7075-T6 aluminum-alloy sheet. Axial-load fatigue-crack-propagation tests were conducted on 12 in. (305 mm) wide sheet specimens made of 7075-T6 aluminum alloy. These tests were made at stress ratios R (ratio of the minimum stress to the maximum stress) ranging from −1.0 to 0.8 and at maximum stress levels ranging from 5 to 50 ksi (34–340 MN/m2) to study the effects of stress ratio on fatigue-crack growth. The fatigue-crack-propagation data were analyzed using Paris' stress-intensity analysis. The data from tests at negative R values fell into a relatively narrow scatterband along with the results from the R = 0 tests on a plot of rate against stress intensity range. Apparently, the compression portion of the loading cycle did not significantly affect crack growth in these tests. The data from tests at different positive stress ratios fell into discrete bands on these plots. These bands varied systematically with R, that is, the higher the stress ratio at a given value of ΔK, the higher the rate of fatigue-crack growth. This spread in rates was small at the lower stress-intensity range, but became progressively larger as the stress-intensity range was increased.

M.T. Milan [4] made an attempt to calculate the strain life of interstitial free this sheet**.** In the present work, the monotonic and low cycle fatigue properties of a thin sheet produced from interstitial free steel containing titanium additions were investigated. A special grip alignment fixture permitted the fatigue tests be conducted under deformation control and completely reversed cyclic strain. The material presented different fatigue behavior for the transverse and longitudinal directions, related to the rolling direction. A comparison between the monotonic and cyclic stress-strain curves in the transverse direction showed that the material exhibits cyclic hardening at all tested strain amplitudes. The strain-life relationship was obtained for the transverse direction; buckling of longitudinal specimens made it impossible to obtain such a relationship.

SHRABANI MAJUMDAR [5] studied the micromechanism of fatigue damage in an interstitial-free (IF) steel sheet using fully reversed stress amplitudes ($\sigma/2$). The stress-life (S-N) curve of the steel sheet has been generated, together with a series of interrupted fatigue tests at each of the chosen σ /2, to study the progress of fatigue damage in terms of the initiation, growth, and coalescence of the fatigue cracks on the surfaces of the sheet specimens using scanning electron microscopy. The steel sheet possesses a higher endurance limit (0.98 times its yield strength (YS)), as compared to conventional low-carbon steel sheets. This is attributed to (1) the occurrence of nonpropagating micro cracks initiating primarily at the inclusions below the endurance limit and (2) a significant delay in the spread of plastic deformation, until $\sigma/2$ is close to YS.

R.D. Noebe [6] Tensile testing of cast and extruded binary NiAl was performed from 300 to 900 K at strain rates of $1.4 \times 10{-}4$ to $1.4 \times 10{-}1 \times s{-}1$. The brittle-to-ductile transition temperature (BDTT) was dependent on strain rate, with a three order of magnitude increase in strain rate resulting in approximately a 200 K increase in transition temperature. Regardless of strain rate, at temperatures just above the BDTT the fracture strength increased significantly and the fracture morphology changed from mostly intergranular to predominantly transgranular. It was also determined that the mechanism responsible for the brittle-to-ductile transition in NiAl had an apparent activation energy of approximately 118 kJ/mol. These results support the argument that the mechanism for the brittle-to-ductile transition in NiAl is associated with the onset of a thermally activated deformation process. This process is probably dislocation climb controlled by short circuit diffusion.

Chapter 3

EXPERIMENTAL PROCEDURE

3. Experimental procedures

3.1 Specimen fabrication

A cold-rolled and batch-annealed Ti-stabilized IF steel sheet of 1.4-mm thickness was collected. Tensile and fatigue test specimens (dimensions are shown in the figure) were fabricated from the thin sheet with an EDM wire cut machine. Longitudinal specimens were cut along the rolling direction of the sheet. A square shaped specimen was machined for microstructural observations.

3.2 Material characterization

The chemical composition and the microstructure of the specimen are given in the Table 3.1 and Fig.3.2.

Table no 3.1 Chemical composition of the selected IF steel (in wt %)

C	**0.0034**
Mn	**0.078**
S	**0.009**
P	**0.012**
Si	**0.006**
Al	**0.0358**
N_2	**0.003**
Ti	**0.065**
Fe	**Balance**

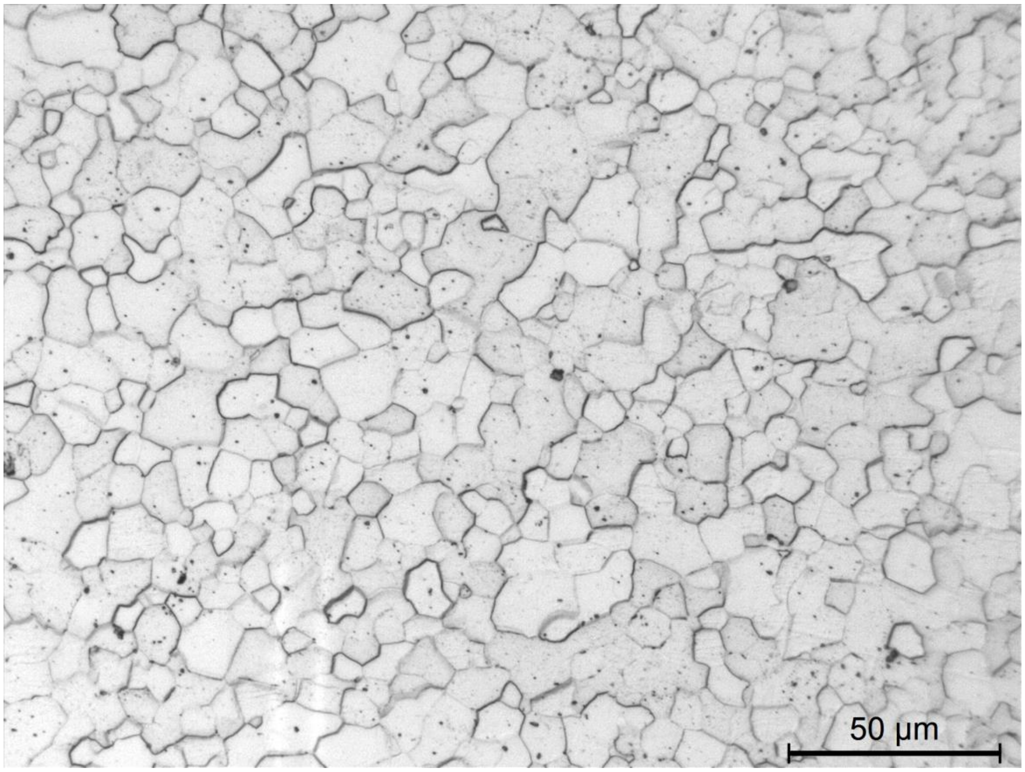

Fig 3.1 (microstructure of IF steel)

3.3 Tensile Testing

Initially tensile testing of the sample (dimension are given in fig .x) was carried out using universal testing machine. A gauge length of 8mm was selected and tensile loading is done with a crosshead velocity of $8*10^{-3}$ mm per sec. Average yield strength value was calculated using the yield strength values of two of the same samples. Then a total of 6 specimens were subjected to tensile testing under different strain rate 10^{-4} , 10^{-3}, 10^{-2} mm per second respectively to observe the effect of strain rate on tensile properties and the changes in tensile properties were analyzed using origin pro 8 software.

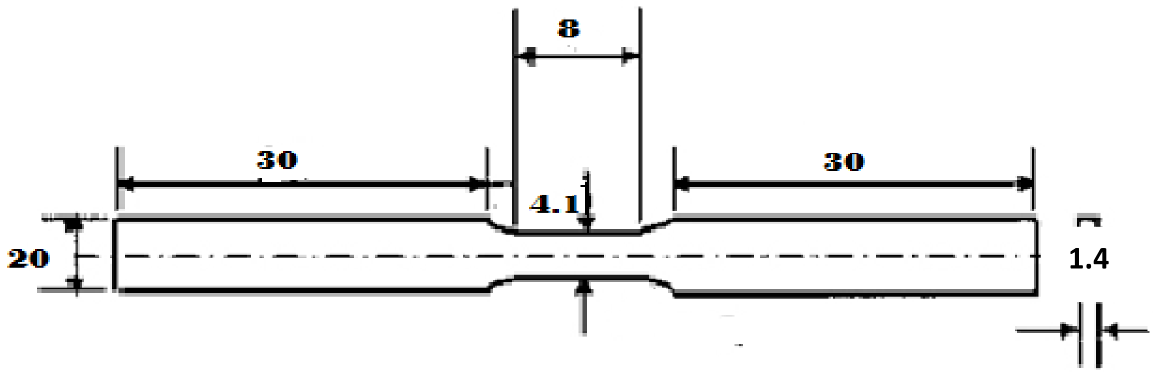

Fig no 3.2(tensile specimen)
(All the specimen dimensions are given in **mm**)

3.4 Fatigue Testing Of As Received Specimens

A test matrix was prepared in accordance with the average yield strength value. High cycle fatigue test was carried out for sixteen samples at different stress ratios and different stress values. The maximum stress was set at 0.9 times the yield strength (average yield strength value was obtained from the tensile testing) of the material initially. A total of 8 specimens were tested at max. stress value of 0.9Y.S then the maximum stress value was raised to 0.95Y.S to observe the change in fatigue behavior of the test specimen. A cyclic load of tension-tension type with a maximum stress of 0.9 Y.S was applied to the specimen using a sinusoidal waveform of frequency 50 Hz. A total of sixteen specimens were subjected to high cycle fatigue test at different stress ratios (0.05, 0.1, 0,2, 0.3) respectively.

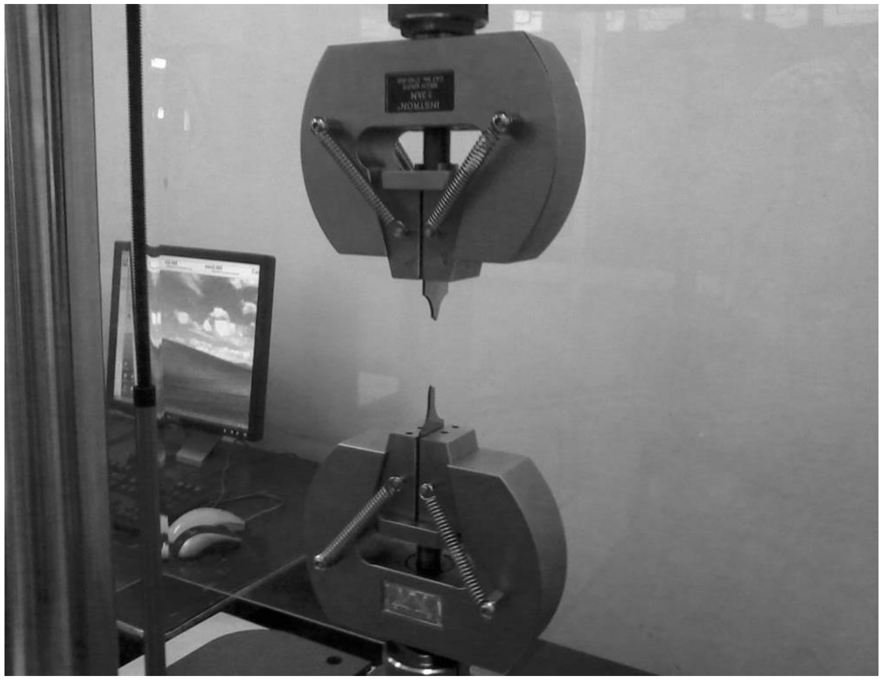

Fig. 3.3 (fractured specimen under fatigue)

Chapter 3

RESULT AND DISCUSSION

4. Results and Discussion

4.1 Tensile Test Results

Table no 4.1

Sample NO	Avg. thickness (mm)	Avg. width (mm)	Gauge length (mm)	Yield strength (Mpa)
1	**1.37**	**4.19**	**8**	**287**
2	**1.38**	**4.18**	**8**	**303**

From the above table yield strength was found to be 295 Mpa.

4.2 Fatigue Testing

The high cycle fatigue testing data of 8 specimens at different stress ratios are given below.

Table no 4.2.

Sample No	Stress ratio	σ_{max} MPa	σ_{min}	Stress amp (MPa)	No of cycles to failure	Remark
1	**0.05**	**265.5**	**13.28**	**126.11**	**487122**	**Failed**
2	**0.05**	**265.5**	**13.28**	**126.11**	**521570**	**Failed**
3	**0.1**	**265.5**	**26.5**	**119.5**	**3430690**	**Failed**
4	**0.1**	**265.5**	**26.5**	**119.5**	**3333552**	**Failed**
5	**0.2**	**265.5**	**53.22**	**105.89**	**18194004**	***Didn't fail***
6	**0.2**	**265.5**	**53.22**	**105.89**	**9380238**	**Failed**
7	**0.3**	**265.5**	**79.85**	**92.81**	**12482679**	***Didn't fail***
8	**0.3**	**265.5**	**79.85**	**92.81**	**13061655**	***Didn't fail***

(fatigue testing data obtained when the σ_{max} value was set at 0.9YS i.e 265.5 MPa and frequency of cyclic load was set at 40 Hz)

Table no 4.3

Sample No	Stress ratio	σ_{max} (MPa)	σ_{min} (MPa)	Stress amp (MPa)	No of cycles to failure	Remark
1	**0.05**	**280.25**	**14.01**	**133.12**	**287231**	**Failed**
2	**0.05**	**280.25**	**14.01**	**133.12**	**434928**	**Failed**
3	**0.1**	**280.25**	**28.02**	**126**	**662805**	**Failed**
4	**0.1**	**280.25**	**28.02**	**126**	**683429**	**Failed**
5	**0.2**	**280.25**	**56.04**	**112.5**	**7404810**	**Failed**
6	**0.2**	**280.25**	**56.04**	**112.5**	**8194573**	**Failed**
7	**0.3**	**280.25**	**84.07**	**98**	**10378375**	***Didn't fail***
8	**0.3**	**280.25**	**84.07**	**98**	**10867594**	***Didn't fail***

(fatigue testing data obtained when the σ_{max} value was set at 0.95YS i.e 280.25 MPa and frequency of cyclic load was set at 40 Hz)

Graphs between the stress ratio vs. the no of cycles to failure and stress amplitude vs. no of cycles to failure were plotted. The results are given in the fig.4.1 and fig.4.2 below.

The no of cycles to failure increased with increasing stress ration and decreased with decreasing stress amplitude value.

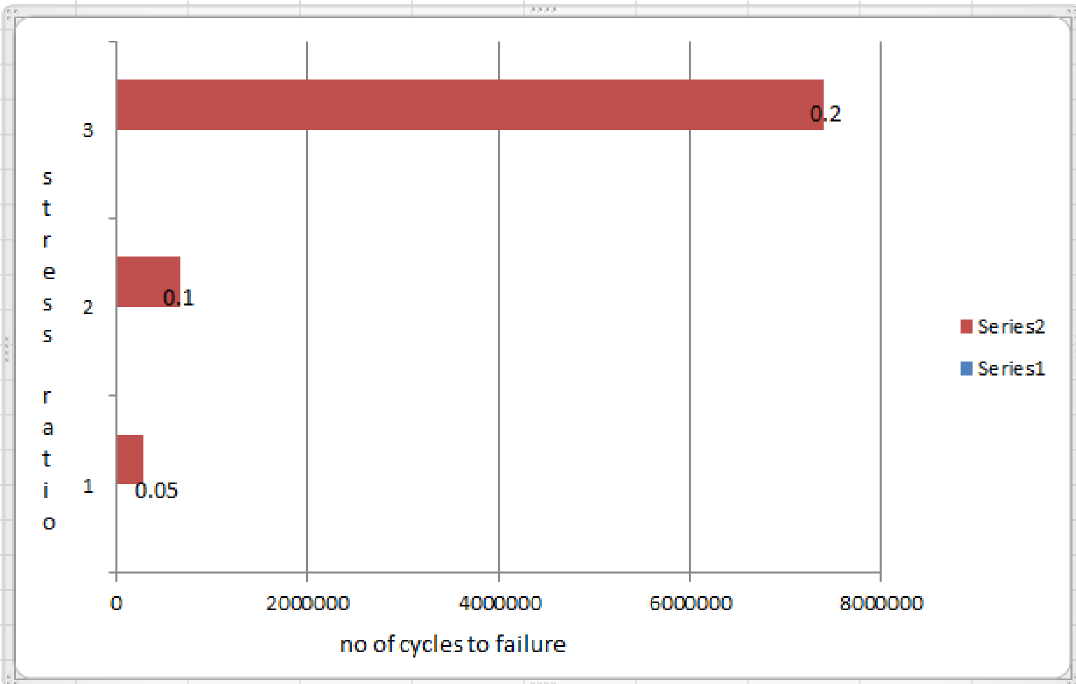

Fig no 4.1

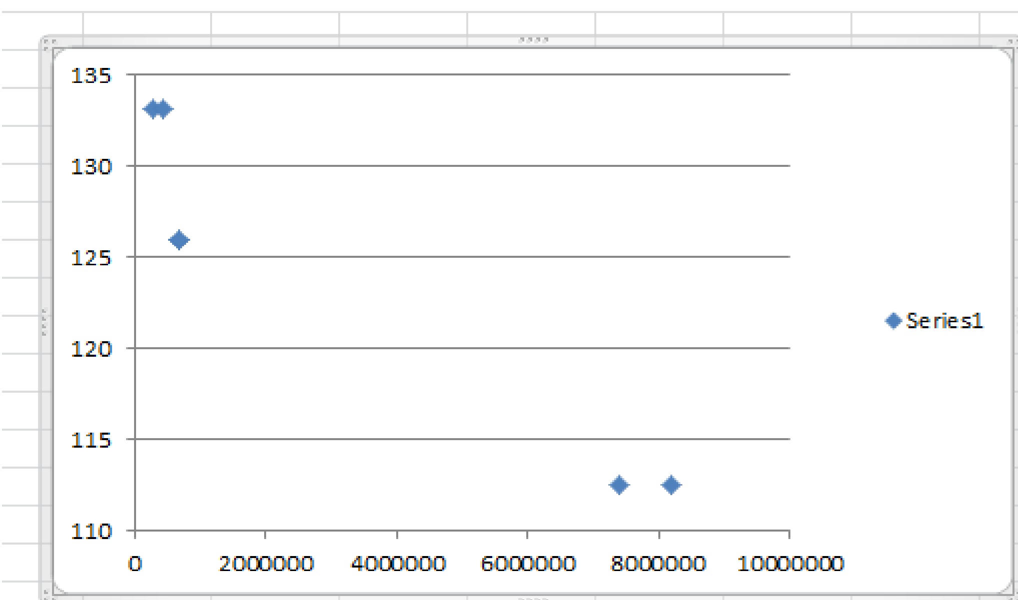

Fig no 4.2

4.3 Effect Of Strain Rate On Tensile Loading

A total of six samples were loaded in a tensile manner with different strain rates like 10^{-4} , 10^{-3}, 10^{-2}mm/sec. An increment in the UTS value was observed as the strain rate kept on increasing. But the area under the stress strain curve decreased with increasing strain rate and the severity of fracture of the specimens increased. The plot of the stress strain plot for two different strain rates are given below in fig no 4.3 and fig no 4.4.

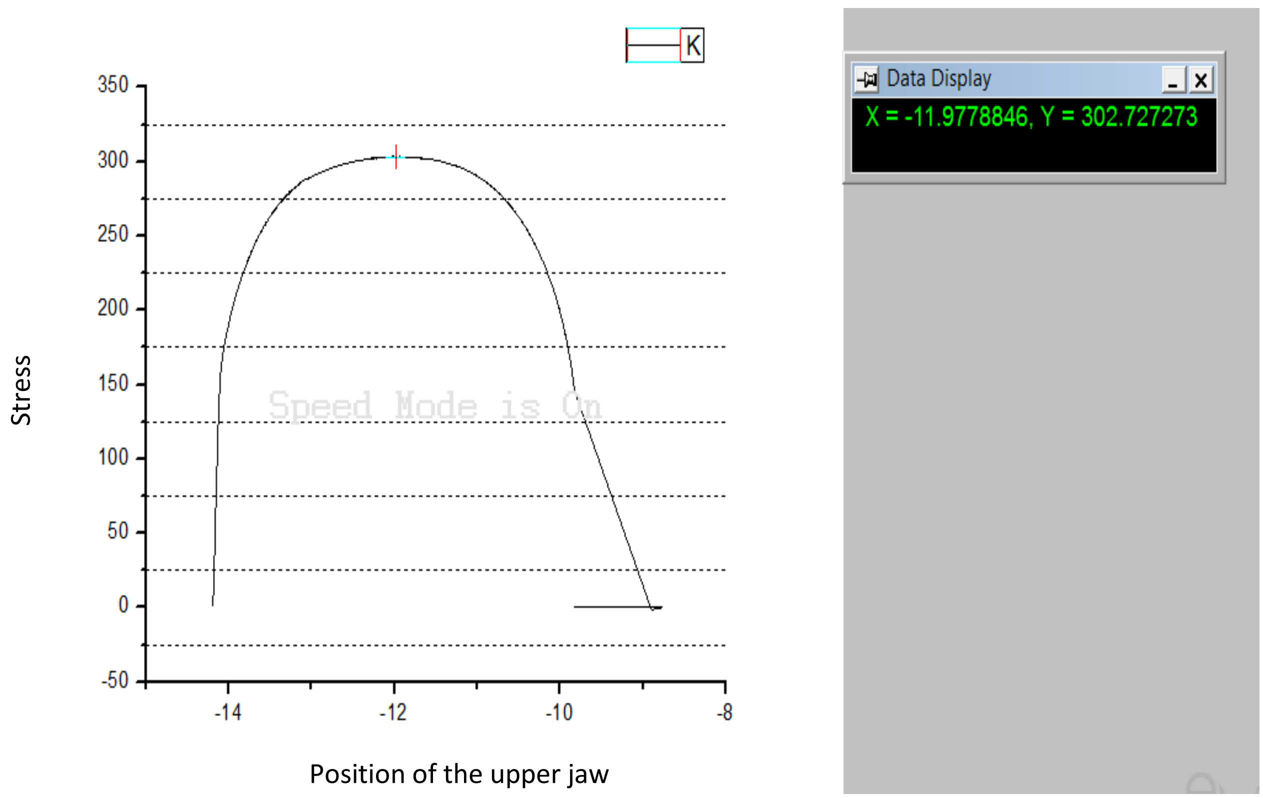

Fig no 4.3

(A plot between the stress and displacement when strain rate was 10^{-4}mm/sec)

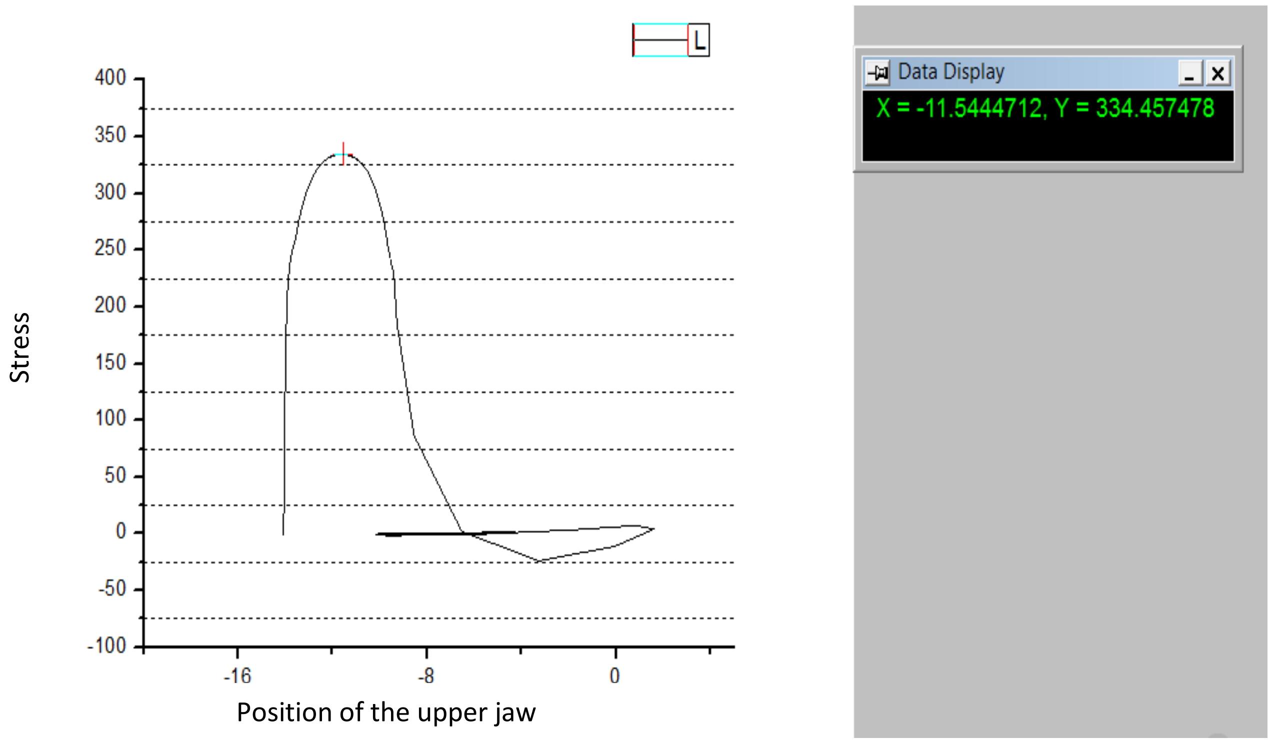

Fig no 4.4

(A plot of stress vs. displacement at strain rate, 10^{-2})

The tensile strength of the specimen increased with increasing strain rate because the rate of generation of dislocations exceeds the rate of diffusion of dislocations through grain boundaries. Hence the dislocation pile up increases so does the strength.

4.4 Fractography and Analysis of Factographs

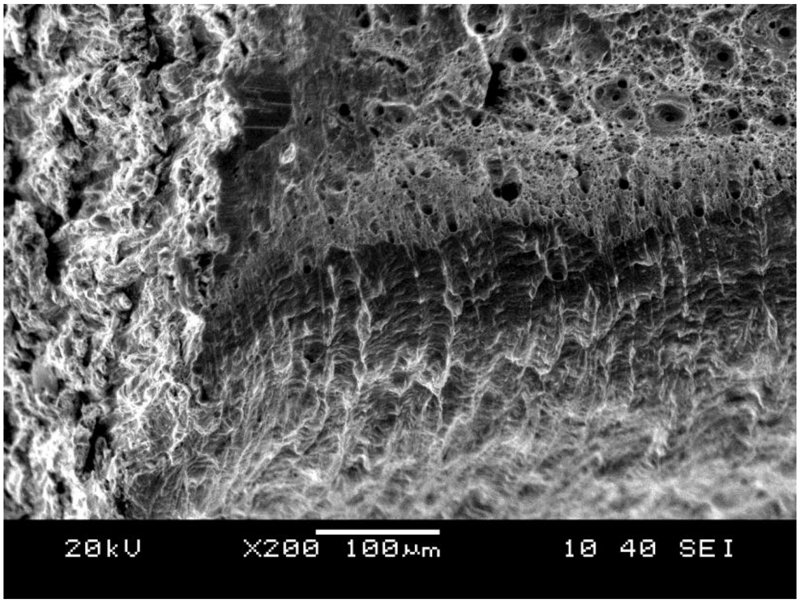

Fig. no 4.5

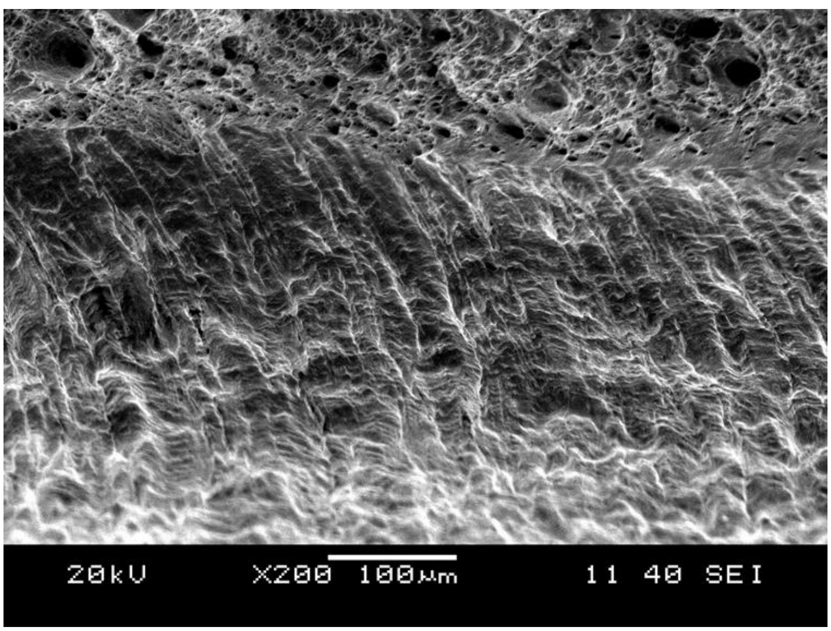

Fig. no 4.6

The fig. no 4.5 & fig no 4.6 represent the SEM fractograph of the specimens which fractured under high cycle fatigue (tension – tension type) with maximum stress being set at 0.95 YS.

Although fatigue crack initiates from the surface, in this case there has not been any evidence of crack propagation from the surface. There are striation marks inside the body.

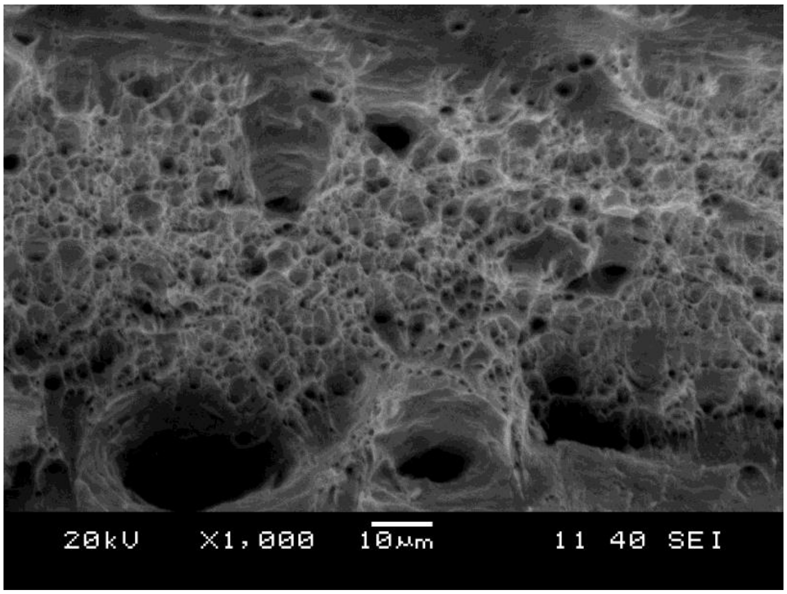

Fig no 4.7

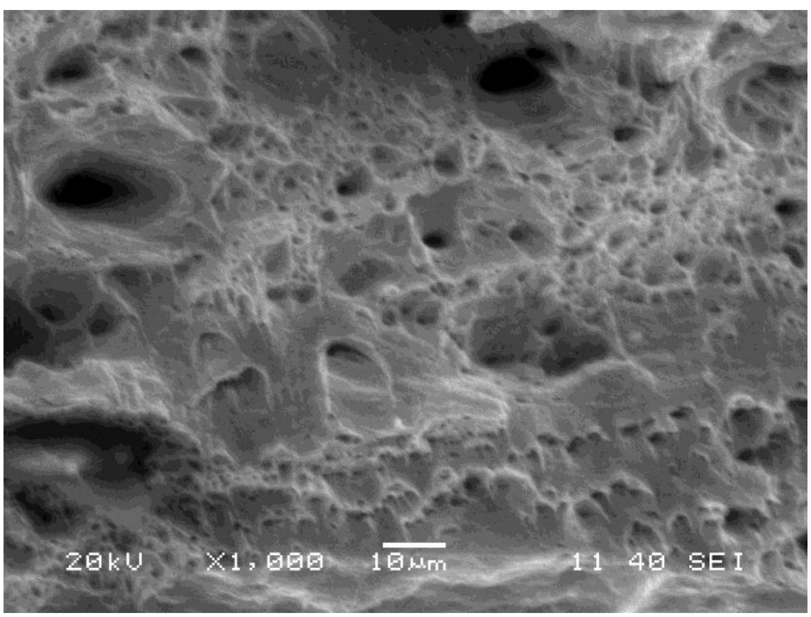

Fig no 4.8

Fig no 4.7 & fig no 4.8 represent the SEM fractographs of the specimen which fractured under tensile loading with strain rates 10^{-4} and 10^{-2} mm/sec respectively.

Fig no 4.7, which represents the fractured surface of the specimen which fractured under tension with a strain rate 10^{-4} mm/sec' has a higher density of dimples. And the dimples are deeper. But the specimen which has been loaded with a strain rate 10^{-2} mm/sec has got shallow dimples and even the density of the dimples is low as well.

Chapter 5

CONCLUSION

5. Conclusion

1. The fatigue life of the specimen increases as the stress ratio increases.
2. The no of cycles to fatigue failure decreases as the stress amplitude increases.
3. The σ_{max} value has also some effect on the fatigue property. The no of cycles to failure decreased as the σ_{max} value is increased from 0.9YS to 0.95 YS.
4. When strain rate of tensile loading is increased the UTS value increased but the total elongation of the specimen before fracture reduced and the fracture occurred in a severe manner.
5. Ductility of the specimen decreased as the strain rate of tensile loading is increased.

Chapter 6

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